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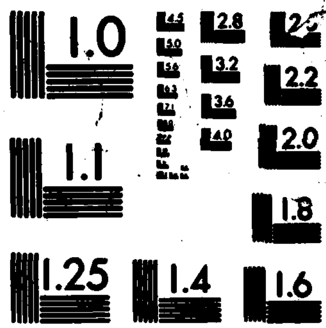

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For more than a dozen years, Doppler tracking of the Navy Navigation Satellite System (NNSS) has demonstrated the ability to give solutions for polar motion as a byproduct of precise ephemerides generation. This paper reviews the polar motion estimation process at the Defense Mapping Agency from Doppler measurements of the NNSS and gives comparisons to polar motion series from newer observational techniques and to the Bureau International de l'Heure (BIH) Cirucular-D series. The different techniques are compared fro the period of the MERIT Main Campaign. In addition to comparing results for the Nova and Oscar NNSS satellites, comparisons are done utilizing the WGS 84 and the NWL 9Z2 gravitational fields in the precise ephemerides generation process.

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INVESTIGATION OF POLAR MOTION FROM DOPPLER TRACKING OF THE NAVY NAVIGATION SATELLITE SYSTEM DURING THE MERIT CAMPAIGN

WILLIAM H. WOODEN, JOHN A. BANGERT, AND J. MILO ROBINSON
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SUMMARY

For more than a dozen years, Doppler tracking of the Navy Navigation Satellite System (NNSS) has demonstrated the ability to give solutions for polar motion as a byproduct of precise ephemerides generation. This paper reviews the polar motion estimation process at the Defense Mapping Agency from Doppler measurements of the NNSS and gives comparisons to polar motion series from newer observational techniques and to the Bureau International de l'Heure (BIH) Circular-D series. The different techniques are compared for the period of the MERIT Main Campaign. In addition to comparing results for the Nova and Oscar NNSS satellites, comparisons are done utilizing the WGS 84 and the NWL 9Z2 gravitational fields in the precise ephemerides generation process.

1.0 INTRODUCTION

Since the late nineteenth century, it has been recognized that the instantaneous spin axis of the Earth moves with respect to the geographic pole of the Earth's crust. This "polar motion" was predicted by Euler in 1752, but was not conclusively observed until Kuenstner's work in 1884-85. The International Latitude Service (ILS) was established in 1899 to continuously monitor the motion of the pole by making systematic determinations of latitude. With the development of new astrometric instruments during the 1950s and their use at the national observatories, it was decided to reorganize the ILS into the International Polar Monitoring Service (IPMS) in 1962 with the charter of deriving polar motion from latitude and universal time data of all astronomical instruments.

The Bureau International de l'Heure (BIH) was created in 1912 to unify time by publishing the time of emission (in universal time) of radio time signals. With the advent of atomic time standards in 1955 and the need to account for polar motion in a timely manner for UT1 determination, the BIH began to determine its own set of coordinates of the pole from latitude data supplied by participating observatories. Until 1972, the BIH used only the same data as the IPMS so a complete overlap of functions with the IPMS existed. Since 1972, pole positions based on Doppler observations of the Navy Navigation Satellite System (NNSS)

satellites have been incorporated into the BIH global solution. The methods used by the BIH in the treatment of data are given by Feissel [1].

Research at the Naval Weapons Laboratory (now the Naval Surface Weapons Center) by Anderle and Beuglass [2] demonstrated that it was possible to use Doppler observations of NNSS satellites to compute pole positions. Doppler solutions of pole position have been distributed by the Dahlgren Polar Monitoring Service since 1969. The pole positions are a byproduct of the orbit computation process. Hence, when the responsibility of computing the NNSS satellite orbits was transferred to the Defense Mapping Agency (DMA) in 1975, the derivation of pole position was continued by DMA. The DMAHTC Polar Monitoring Service (DPMS) reports are distributed by the Hydrographic/Topographic Center of DMA to users on a weekly or monthly basis.

Project MERIT [3] was a program of international collaboration to monitor Earth rotation and intercompare techniques of observation and analysis. The MERIT Main Campaign of observations was held during the period September 1, 1983, to October 31, 1984 and included a variety of techniques for determining polar coordinates.

2.0 COMPUTATIONAL METHODS FOR DOPPLER DATA

The pole determination method utilized by DMA is the method adopted by the Naval Surface Weapons Center (NSWC) in August 1971. The brief description of the method that follows is taken from the detailed description of the observational procedures and the data reduction techniques given by Anderle [4].

Doppler observations are made daily by a network of approximately [illegible] worldwide tracking stations controlled by DMA and a network of 4 U.S. tracking stations controlled by the Navy Astronautics Group. All observations taken in a 48-hour period are processed with the CELEST computer program [5]. A least-squares solution is obtained which includes the six constants of orbital integration, a drag scaling factor for each day, a frequency and a tropospheric refraction scaling factor for each pass, the two components of the pole position, and the coordinates of any mobile observing station. The least-squares solution is based on differences between the observations and computed data, which correspond to a predicted satellite orbit. The initial conditions for the equations of motion come from the [illegible]. The integration scheme is a [illegible]-order Cowell with a one-minute stepsize. The mathematical model includes the Earth's gravitational field, atmospheric drag, solar radiation pressure, luni-solar

gravity perturbations, and solid Earth tidal forces. The integration is done in the true-of-date system.

The accuracy of the orbit determination process is reflected by two statistics: the discontinuity in the ephemeris at the ends of each 2-day span and the root mean square of the residuals of the least-squares adjustment process. The current accuracy of the ephemerides is approximately three meters according to Murphy and Fell [6]. This value agrees with the previous values given by Bowman and Leroy [7] and Wooden [8].

During the MERIT Campaign, four NNSS satellites were used at DMAHTC: three "Oscar-type" satellites (DMA 60=1967-92A, DMA 68=1970-67A, and DMA 59=1967-48A) and one "Nova-type" satellite (DMA 105=1981-44A). The Nova satellite is equipped with sensors and thrusters which compensate for non-conservative forces in the direction of the velocity vector. Thus, polar motion results from the Nova satellite are largely unaffected by variations in solar activity.

3.0 ANALYSIS OF DOPPLER POLAR MOTION VALUES

The most important components of polar motion are terms with a Chandler period (420-435 days) and terms with an annual period. The annual motion is believed to be due to seasonal variations such as meteorological effects of changes in air masses over the Earth and changes in vegetation and snow loading. The Chandler motion is a consequence of the fact that the inertial spin of the Earth is about an axis other than its principal axis of inertia.

In an attempt to highlight other geophysical properties of the motion and instrumental errors between series of Earth orientation parameters, the dominant annual and Chandler motions and a bias were removed by fitting a five-parameter expression of the following form to each component of polar motion:

$$f(t) = A_1 + A_2 \cos A + A_3 \sin A + A_4 \cos C + A_5 \sin C \qquad (1)$$

where $A = (2\pi t/365.25)$

$C = (2\pi t/435)$

A_1, A_2, A_3, A_4, A_5 = coefficients of the fit

In the analysis that follows, the two types of NNSS satellites are compared with each other and the BIH Circular-D values. Special data sets are created for comparison with other Earth orientation parameter series.

3.1. COMPARISON OF OSCAR-TYPE AND NOVA-TYPE NNSS SATELLITES

The differences between the bi-daily values for each individual NNSS satellite and the BIH Circular-D values for the MERIT period are shown in Figure 1. Unfortunately, only the Nova satellite (DMA 105) has observations for the entire MERIT timespan. Although the x and y curves for this satellite have different biases, they show similar behavior with a time offset of approximately 30 days. The x components of Oscar satellites, DMA 59 and DMA 60, tend to follow the Nova satellite curve, while DMA 68 appears to have periodic oscillations about a constant offset. The y components of the Oscar satellites show less variation than the x components. The scatter associated with the Nova satellite values is much smaller than the scatter in the Oscar satellite values. The statistics associated with these comparisons are given in Table 1. The means and standard deviations in the table are in arc seconds. The number of observations is given in the column labeled n. The second set of means and standard deviations in Table 1 ~~is~~ are taken from the study by Colquitt, Stein, and Anderle [9].

TABLE 1. STATISTICS FOR THE OSCAR - NOVA COMPARISONS

SERIES	X-MEAN	SIGMA-X	Y-MEAN	SIGMA-Y	N	X-MEAN	SIGMA-X	Y-MEAN	SIGMA-Y
105-BIH	-.009	.015	.007	.015	217				
59-BIH	.005	.016	.007	.013	65				
60-BIH	-.003	.025	.002	.016	103				
68-BIH	-.010	.018	.012	.015	154				
68-60	-.007	.031	.010	.022		-.008	.037	.015	.031
59-60	.008	.024	.004	.021		-.007	.029	.001	.023
105-60	-.006	.023	.005	.022		-.009	.026	.010	.024

In addition to examining the raw observations of the individual satellites, special data sets of 5-day means were created from the individual bi-daily values for the Oscar satellites and for the Nova satellite to make comparisons on the standard polar motion days. These two data sets are designated NOVA and OSCAR. Using these special data sets, the biases and the annual and Chandler motions were removed from the observations by means of Equation 1. Figure 2 gives the differences between the residuals of the fits. The largest differences occur between 200 and 300 days into the MERIT timespan. The statistics associated with these fits will be given in the next section.

3.2 COMPARISON OF DOPPLER SATELLITE OBSERVATIONS WITH OTHER EARTH ORIENTATION DATA TYPES

To examine the geophysical information in each Earth orientation series, separate least-squares fits for the x and y components of pole position were made using Equation 1

FIGURE 1. DIFFERENCES BETWEEN NNSS AND BIH POLE VALUES

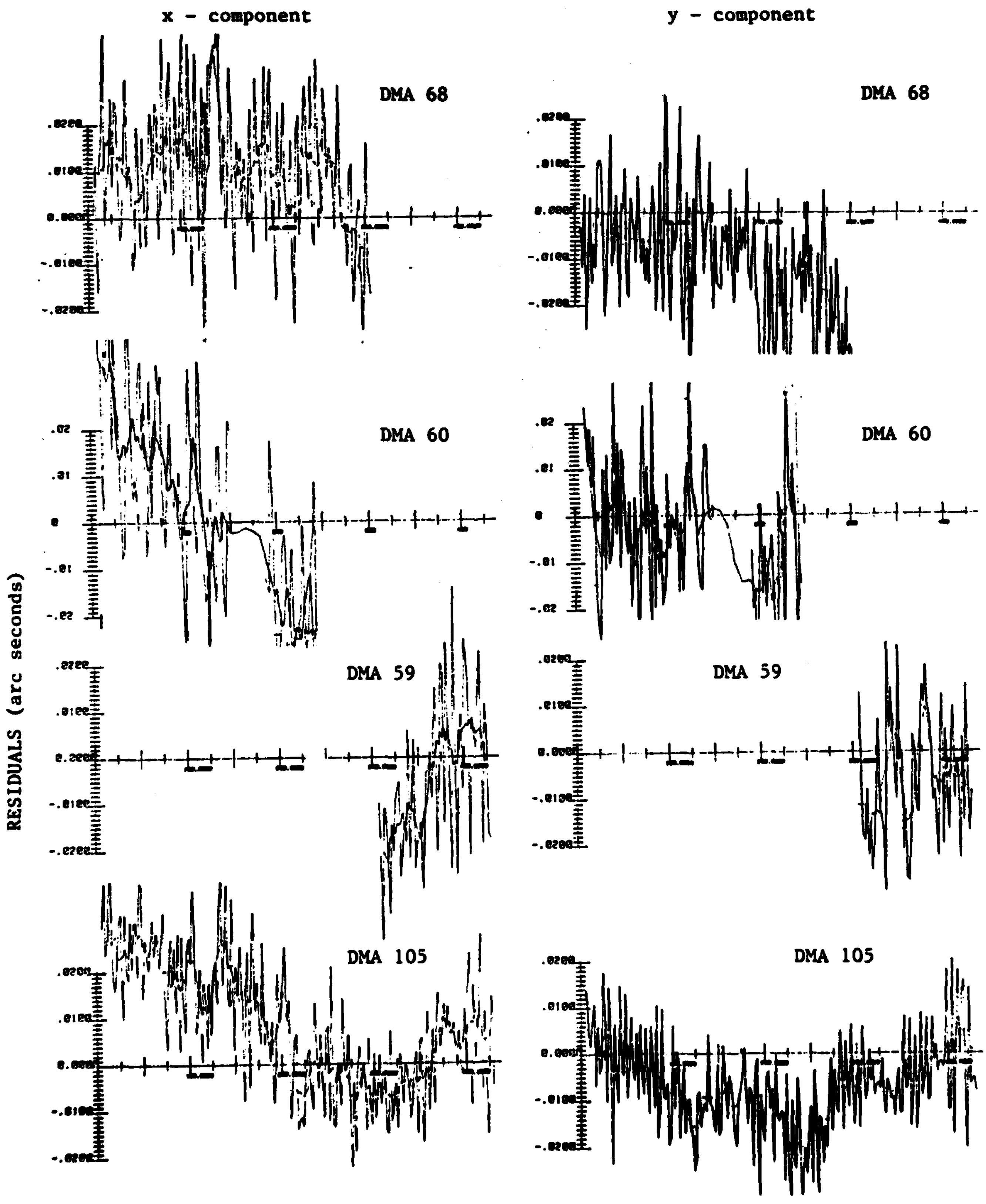
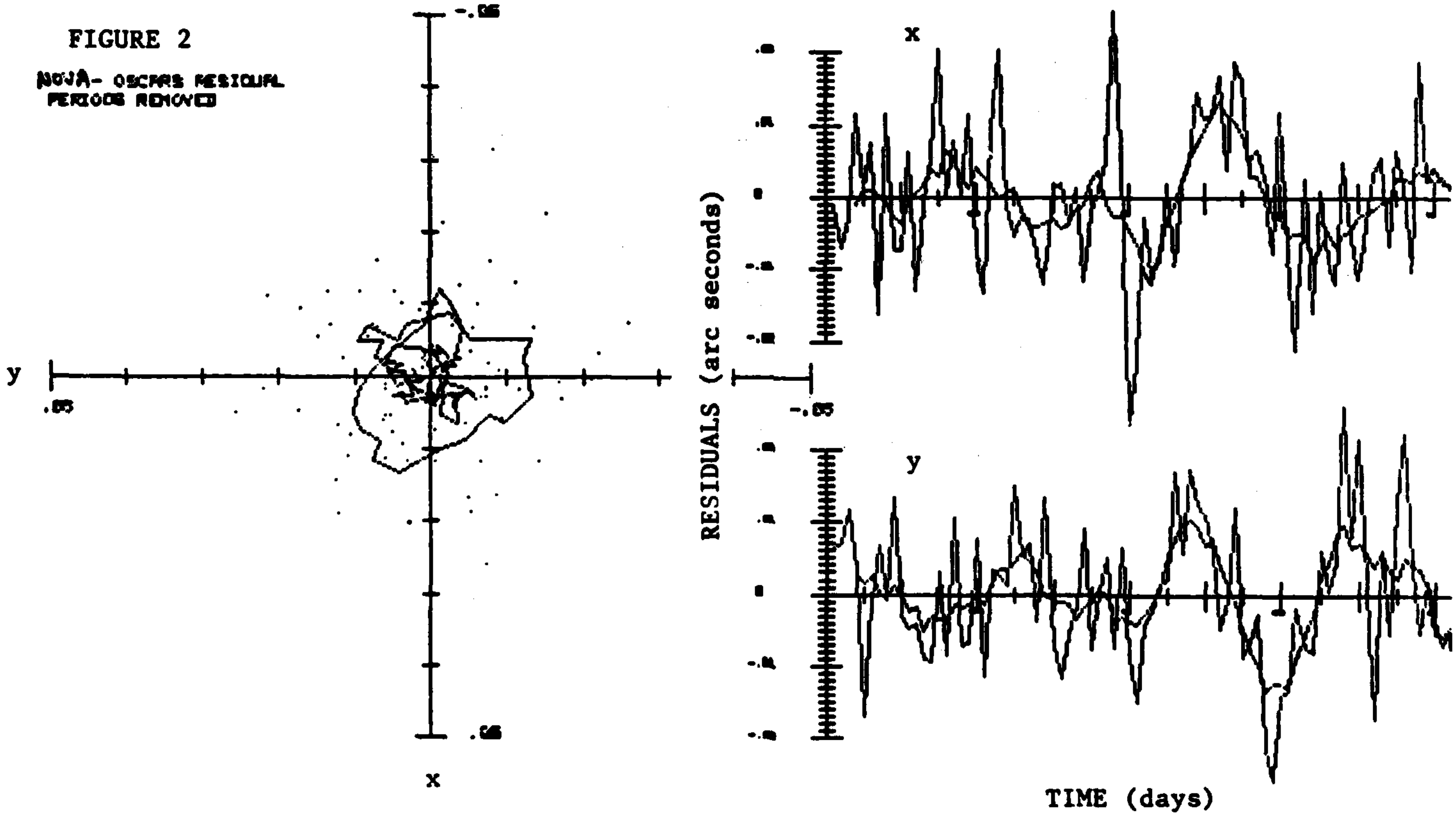


FIGURE 2

NOAA- OSCARS RESIDUAL
PERIODS REMOVED



to remove the annual and Chandler information. The five free parameters of the fits were the mean position of the pole and the amplitudes of the sine and cosine terms of the annual and Chandler motions. Table 2 gives the results of these fits for each data type. The entries of Table 2 are expressed in arc seconds. The BIH series is the Circular-D final values. SLR is the satellite laser ranging series of the University of Texas. VLBI is the Very Long Baseline Interferometry series of the National Geodetic Survey. The SLR and VLBI data were taken from a magnetic tape provided by the US Naval Observatory. DMA is the normal combined solution of weighted means of individual satellites published by DMA on 5-day intervals in the DPMS reports. NOVA and OSCAR are the special 5-day means discussed previously.

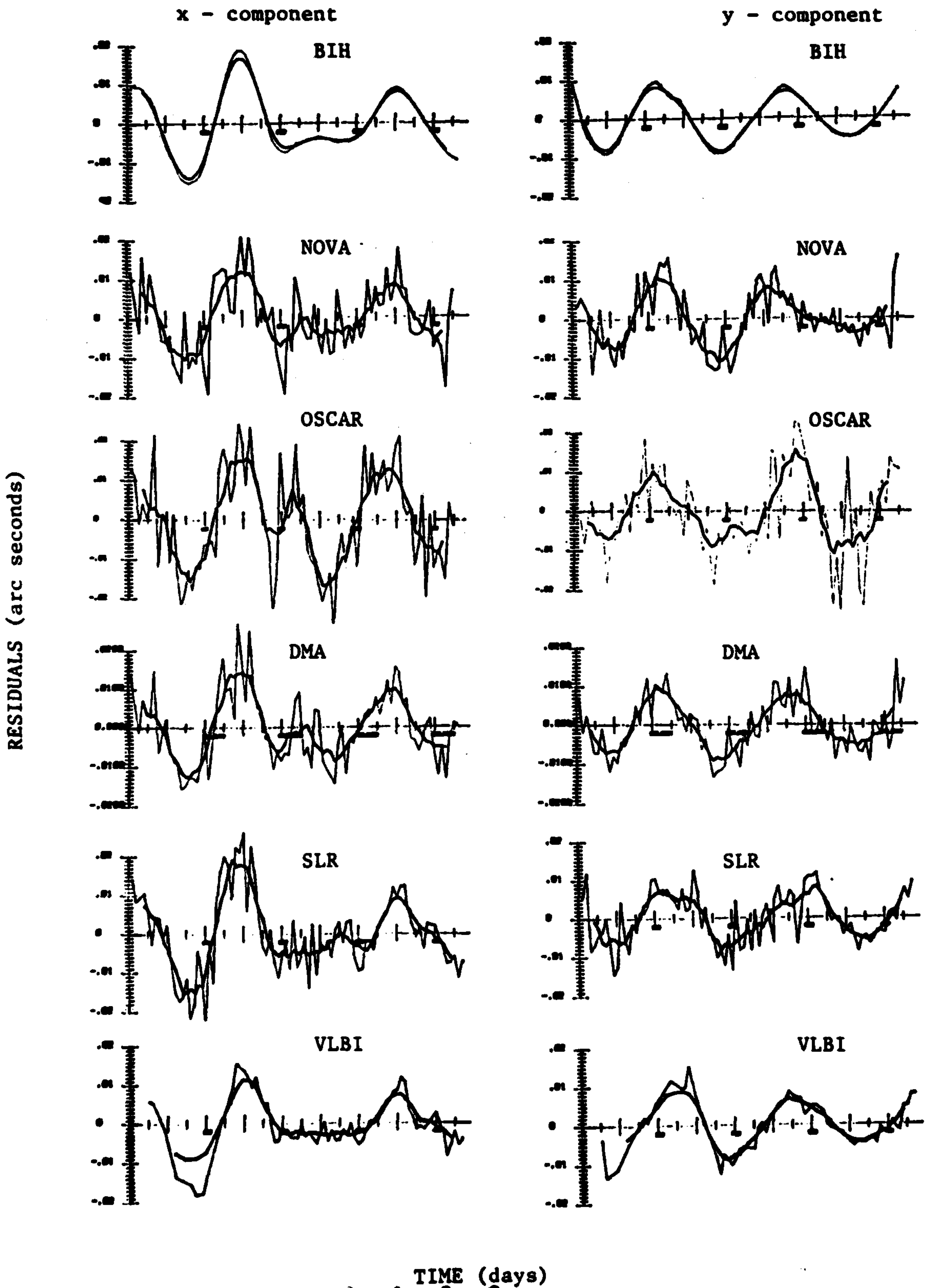
TABLE 2. AMPLITUDES OF THE FITTED PARAMETERS

	x - component						y - component					
Data Set	bias	cos A	sin A	cos C	sin C	sigma	bias	cos A	sin A	cos C	sin C	sigma
BIH	.046	.059	-.008	.206	-.093	.008	.282	.014	-.057	-.115	-.178	.006
SLR	.046	.062	-.016	.206	-.083	.010	.272	.012	-.050	-.115	-.185	.007
VLBI	.046	.073	.008	.178	-.107	.006	.277	.004	-.059	-.114	-.180	.006
DMA	.039	.064	.002	.193	-.105	.009	.289	.017	-.059	-.120	-.178	.007
NOVA	.036	.060	.004	.192	-.114	.009	.287	.021	-.051	-.133	-.178	.007
OSCAR	.039	.074	.008	.182	-.108	.013	.289	.019	-.060	-.125	-.179	.010

Figure 3 shows the residuals of the fits whose fitted parameters are given in Table 2. The smooth line in each plot represents a 7-point moving average of the quantity being plotted. As is evident from the figure, the geophysical information is similar for all data types, i.e., the major peaks agree. All the plots of the Y value residuals exhibit a semiannual period although the OSCAR residuals show an extra hump at 200 days. The X component does not exhibit a semiannual period, but has a distinct signature. The differences in the plots occur between 200 and 300 days. BIH and VLBI are relatively flat in that interval, whereas all the other data sets have a small peak. SLR has its peak at 275 days and NOVA has its peak at 230 days. Again the OSCAR residuals are most different with a large peak at 215 days. Paquet, Djurovic, and Techy [10] also note the similarity of the geophysical information in their residual plots.

To further differentiate subtle differences between the Earth orientation parameter series shown in Figure 3, the residuals of the fits were differenced. The results of this process are shown in Figures 4 through 9. Note that Figure 2 presents results of this process for the NOVA and OSCAR series.

FIGURE 3. RESIDUALS OF THE FIVE-PARAMETER FITS FOR THE EOP SERIES



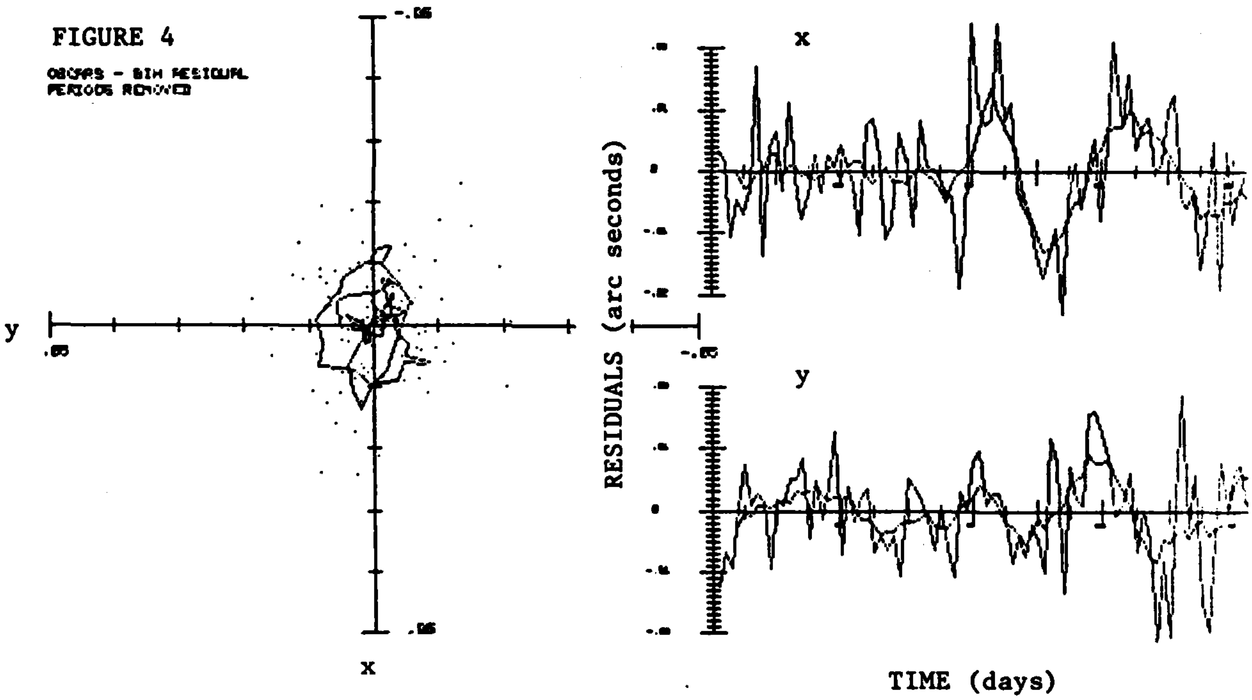


FIGURE 4
OBCARS - BIH RESIDUAL
PERIODS REMOVED

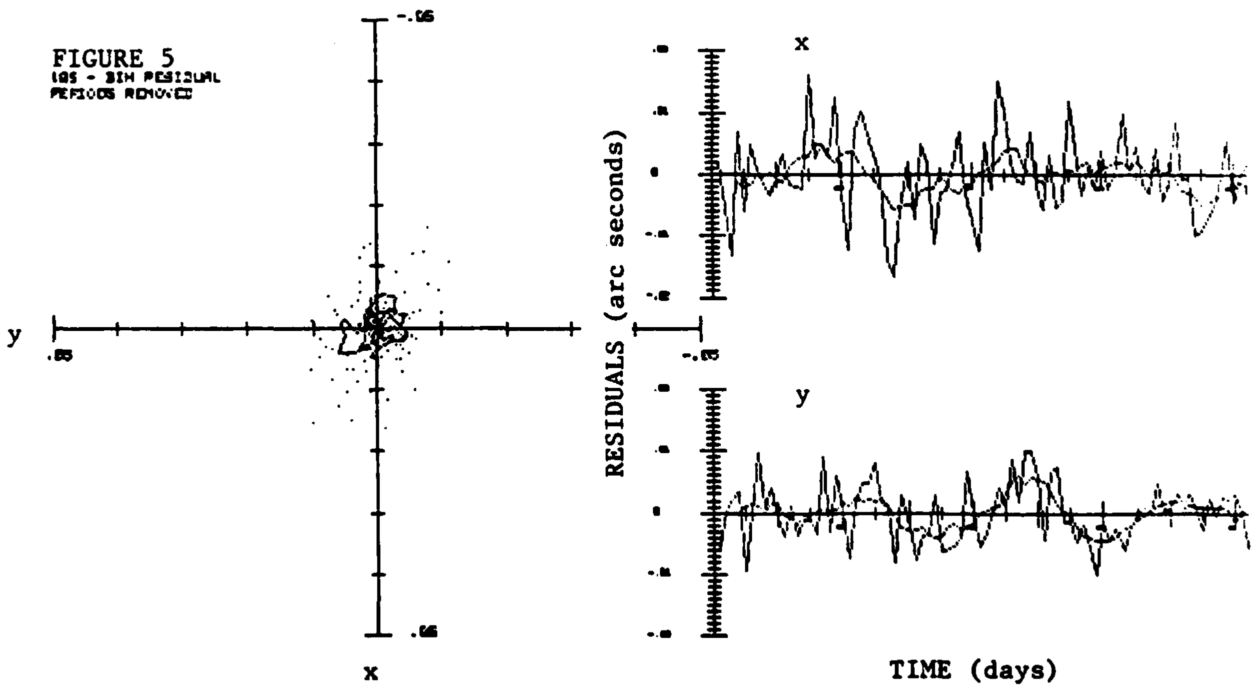


FIGURE 5
IRS - BIH RESIDUAL
PERIODS REMOVED

FIGURE 6

OBCARS - SLR RESIDUAL
PERIODS REMOVED

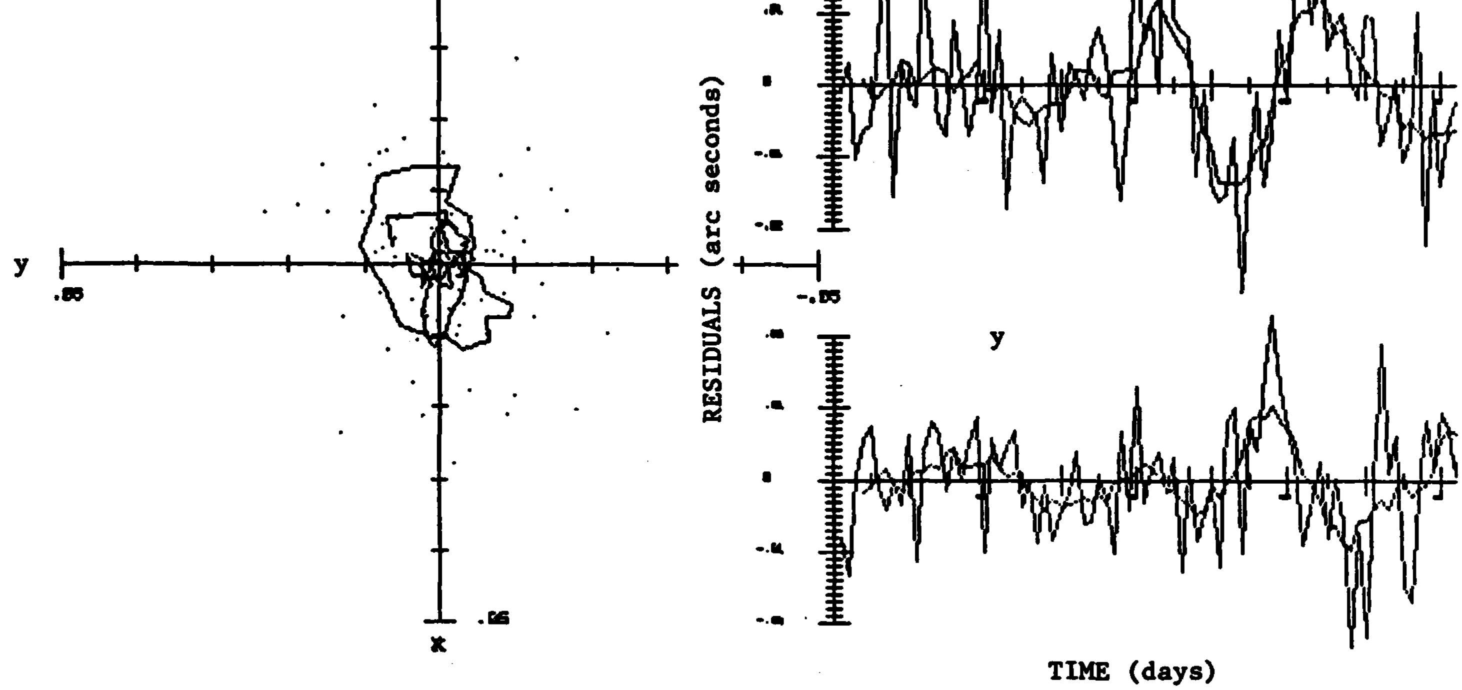


FIGURE 7

IOS - SLR RESIDUAL
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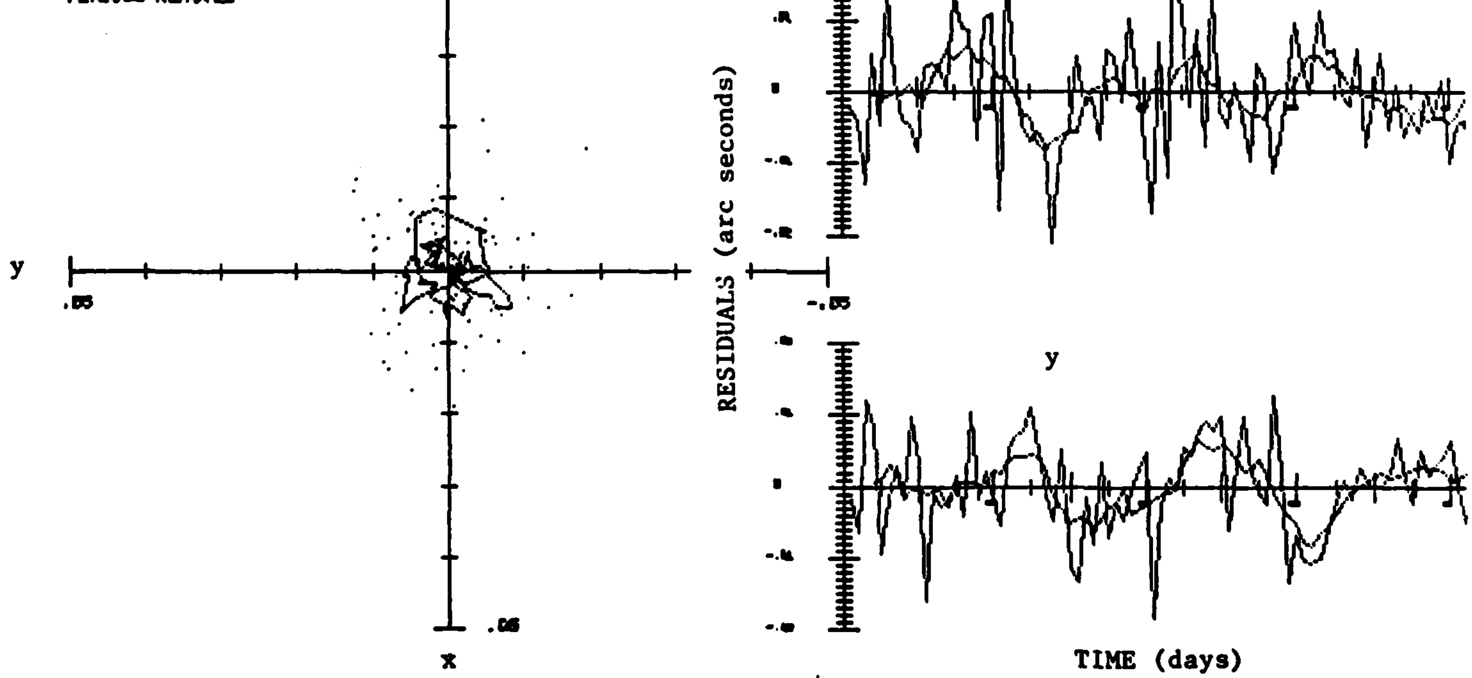


FIGURE 8
OBCARS - VLBI RESIDUAL
PERIODS REMOVED

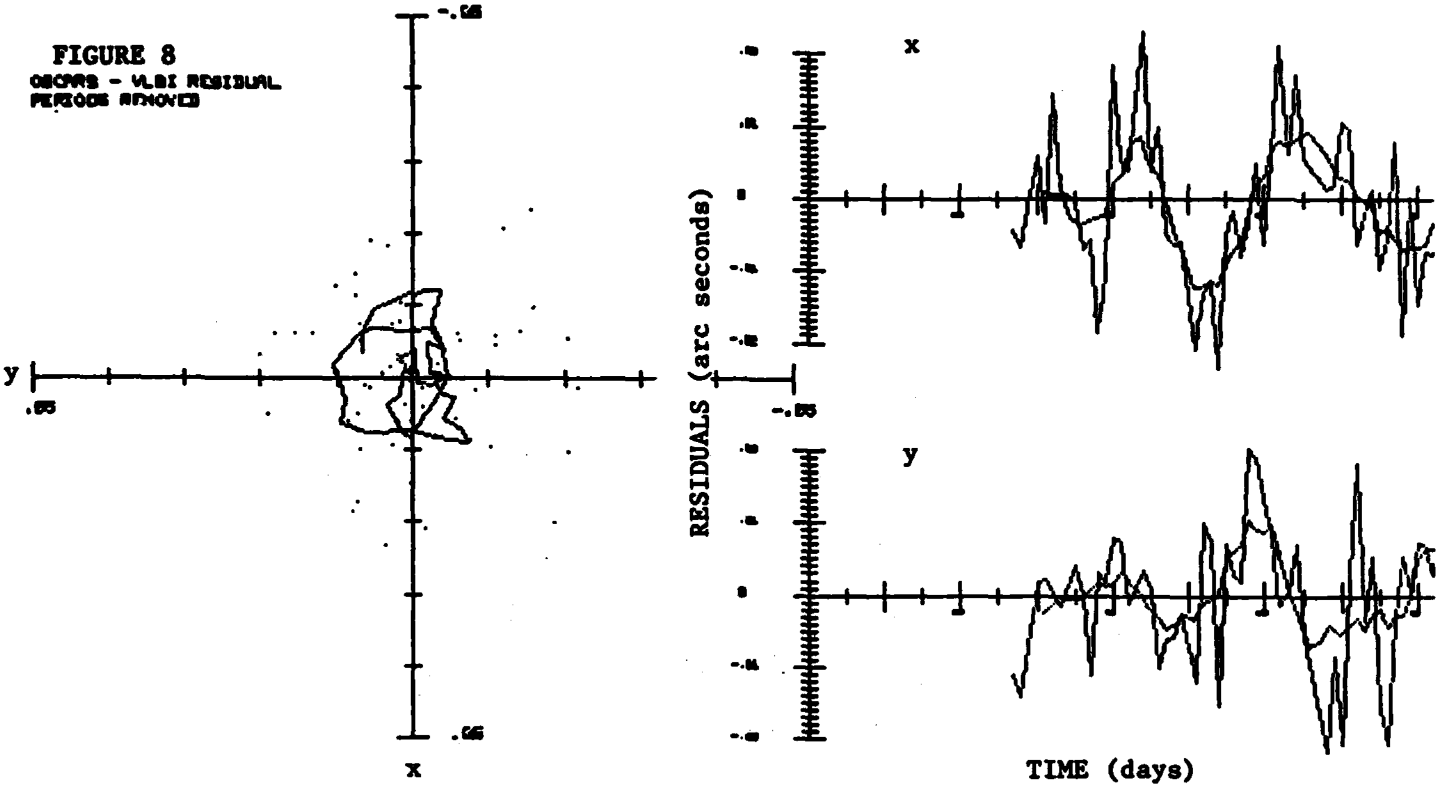
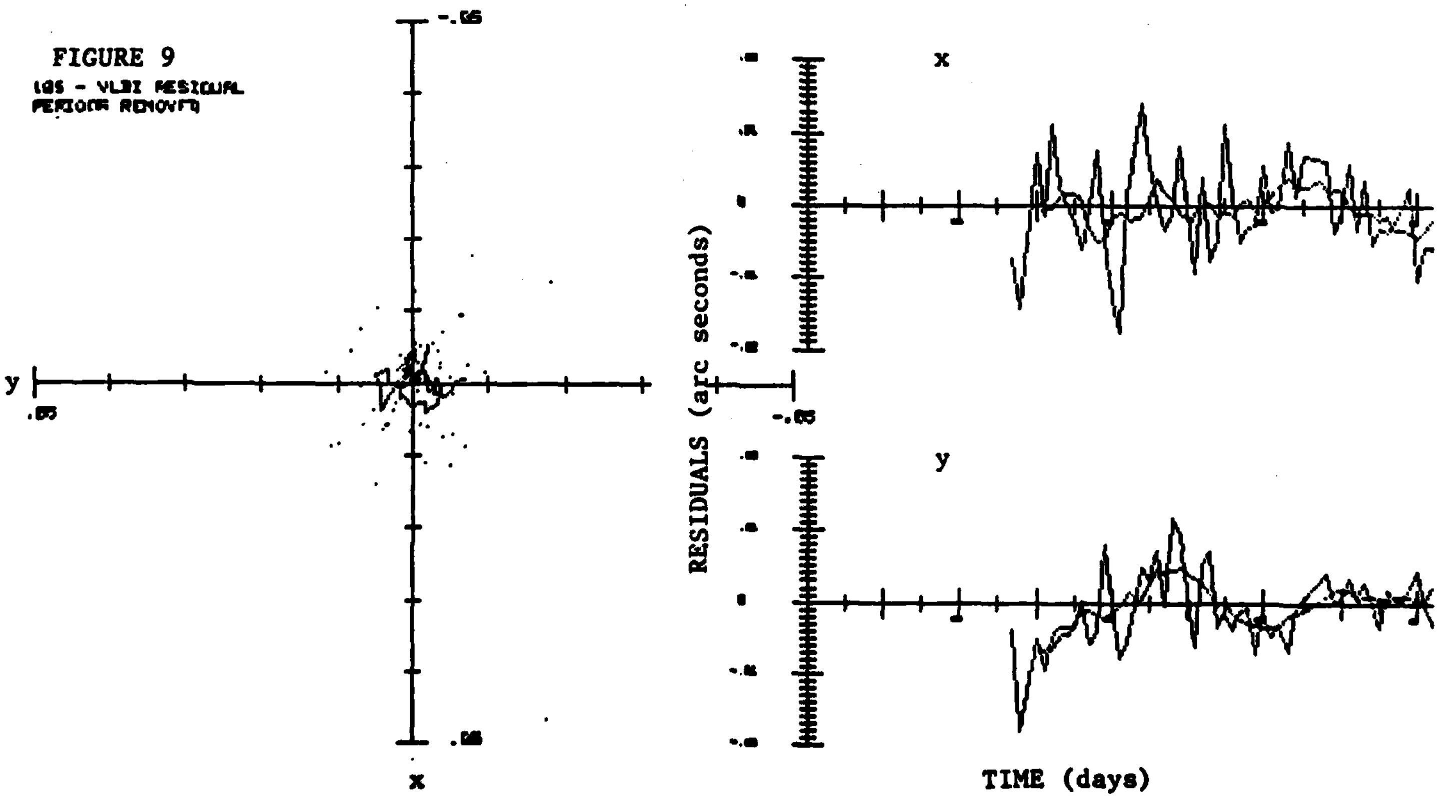


FIGURE 9
IGS - VLBI RESIDUAL
PERIODS REMOVED



4.0 PRELIMINARY EVALUATION OF POLE POSITIONS COMPUTED USING WORLD GEODETIC SYSTEM 1984

Biases between polar motion solutions using different NNSS satellites have been shown to result from uncertainties in knowledge of the Earth's gravity field [11]. The question arises as to whether the development of the World Geodetic System 1984 (WGS 84) and its associated Earth Gravitational Model (EGM), as discussed by Decker [12] and White [13], can improve the pole position solutions. As part of tests ~~of~~ ephemeris generation using WGS 84 (see, for example, [14]), a number of NNSS ephemerides based on WGS 84 have been computed at DMAHTC using the CELEST program. Of particular interest was an interval, beginning in late May and ending in early July 1985, within which WGS 84 precise ephemerides for 5 NNSS satellites were produced on a regular basis. At the same time, analogous precise ephemerides in the NWL 9Z2 system using the NWL 10E-1 EGM were produced as part of DMAHTC routine production. This situation permitted a preliminary comparison of the pole position solutions computed in the two systems.

4.1 PROCEDURES FOR GENERATING WGS 84 BASED SOLUTIONS

WGS 84 versions of CELEST input files were utilized to produce precise ephemerides of 5 NNSS satellites, from day 149 to day 154 and from day 161 to day 179, in 1985. The program input included the WGS 84 EGM truncated to degree (n) and order (m) 41, as well as the WGS 84 ellipsoid parameters. The program also utilized a file of WGS 84 tracking station coordinates which were obtained by applying a geometric transformation to the "production" NWL 9Z2 coordinates. Each orbit fit for satellites DMA 59, DMA 77, DMA 93, and DMA 115 (Nova) was based on 2 days of tracking data, while each fit for satellite DMA 105 was based on 1 day of data.

During the test period, DMAHTC also produced precise ephemerides of the same 5 NNSS satellites for routine production purposes. These fits utilized the NWL 10E-1 EGM (n=28, m=27) and the NWL 9Z2 tracking station coordinate set. Data editing occurred independently in the analogous CELEST solutions in the two systems (i.e., no attempt was made to enforce common data between the solutions).

The pole coordinates output in the two systems were compared to BIH Circular-D values of x and y. Daily values were derived from the BIH 5-day values by cubic spline interpolation, and differences were formed between the interpolated values and the Doppler-derived values. These differences were computed in the sense Doppler minus BIH. The pole position solutions which resulted from the

Table 3: Statistics of the Differences Between the Doppler-Derived Pole Coordinates and the BIH Pole Coordinates

SAT.		Δx (arcsec)		Δy (arcsec)	
		NWL 9Z2	WGS 84	NWL 9Z2	WGS 84
59 n=11	$\bar{\Delta}$ σ	+.0020 ±.0239	+.0147 ±.0264	+.0218 ±.0180	+.0242 ±.0195
77 n=13	$\bar{\Delta}$ σ	-.0016 ±.0215	+.0120 ±.0189	+.0191 ±.0193	+.0195 ±.0182
93 n=11	$\bar{\Delta}$ σ	+.0304 ±.0123	+.0342 ±.0155	+.0269 ±.0094	+.0256 ±.0154
105 n=21	$\bar{\Delta}$ σ	+.0138 ±.0162	-.0053 ±.0101	-.0032 ±.0113	+.0048 ±.0107
115 n=13	$\bar{\Delta}$ σ	+.0160 ±.0189	+.0068 ±.0138	+.0374 ±.0198	+.0180 ±.0063

Table 4: Statistics of Pole Coordinate Differences Grouped By NNSS Types

Satellite Type		Δx (arcsec)		Δy (arcsec)	
		NWL 9Z2	WGS 84	NWL 9Z2	WGS 84
OSCARs (59,77,93) n=35	$\bar{\Delta}$ σ	+.0096 ±.0241	+.0198 ±.0224	+.0224 ±.0163	+.0229 ±.0175
NOVAs (105,115) n=34	$\bar{\Delta}$ σ	+.0147 ±.0170	-.0007 ±.0129	+.0123 ±.0250	+.0099 ±.0112

Notes: $\bar{\Delta}$ = mean difference

σ = standard deviation

n = number of orbit fits

satellite DMA 105 fits (in both systems) on day 175 were outliers and were rejected from further study.

4.2 PRELIMINARY RESULTS OF WGS 84 - BASED POLE SOLUTIONS

Table 3 presents statistics of the differences between the BIH and the Doppler-derived pole coordinates on a satellite-by-satellites basis. An examination of this table gave no conclusive evidence that use of WGS 84 systematically improved the agreement between the Doppler-derived values and the BIH values. However, when the satellites were grouped by type (i.e., Nova and Oscar), as in Table 4, a possible correlation emerged. While the pole positions determined using the Oscar satellites and WGS 84 showed no improvement in agreement with the BIH values, pole positions determined using the Nova satellites and WGS 84 did show better agreement with BIH. Additionally, there was less scatter in the Nova differences when WGS 84 was utilized, as evidenced by the smaller standard deviations.

5.0 CONCLUSIONS

The polar motion derived from Doppler tracking of the NNSS satellites has provided and continues to provide valuable Earth orientation information. When the annual and Chandler components of polar motion are removed from the observational data of each Earth orientation series, the same geophysical information remains. Nova-type NNSS satellites provide more precise estimates of pole position than Oscar-type NNSS satellites. Preliminary analysis shows that the use of WGS 84 may improve the accuracy of the pole positions derived from the Nova satellite orbit fits, but that its use for Oscar satellites does not lead to improved accuracies. However, more data need to be processed to substantiate these preliminary results.

6.0 ACKNOWLEDGMENTS

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END